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(12) UK Patent Application (19) GB (11) 2 334 139 (13) A

(43) Date of A Publication 11.08.1999

(21) Application No 9802332.8

(22) Date of Filing 05.02.1998

(51) INT CL[6]
H05H 7/12 9/04

(52) UK CL (Edition Q)
H1D DL D18AY D18A1AY D18A1A2 D18A1BY D18A1B2B D18A1B2Y D18A1Y D19X D19Y D20HY D20H2 D20N D20S D50

(56) Documents Cited
GB 0599129 A GB 0530785 A US 4629938 A

(58) Field of Search
UK CL (Edition P) H1D DKAK DKGA DKGB DKGC DL
INT CL[6] H01J 23/18 23/20 23/207 23/213 , H05H 7/12 7/14 7/18 7/20 9/00 9/04

(71) Applicant(s)
Elekta AB (Publ)
(Incorporated in Sweden)
Box 7593, SE-103 93, Stockholm, Sweden

(72) Inventor(s)
John Allen
Leonard Knowles Brundle
Terry Authur Large

(74) Agent and/or Address for Service
Fry Heath & Spence
The Old College, 53 High Street, HORLEY, Surrey, RH6 7BN, United Kingdom

(54) Abstract Title
Linear Accelerator

(57) A linear standing wave accelerator, for an electron beam, comprises a series of accelerator cavities (10,12,14) which are coupled by way of coupling cavities (16, 18). The energy of the electron beam is adjusted by the extent of coupling between the adjacent accelerator cavities. The extent of coupling is varied by the rotation of an element (20) within at least one coupling cavity (18). One embodiment of the invention has a cylindrical coupling cavity (18) with a rotatable element (20) free to rotate about its own axis of symmetry and that of the cavity. This device allows the variation of the coupling between two points in an RF circuit whilst maintaining the RF phase relationship and varying the relative magnitude of the RF fields.

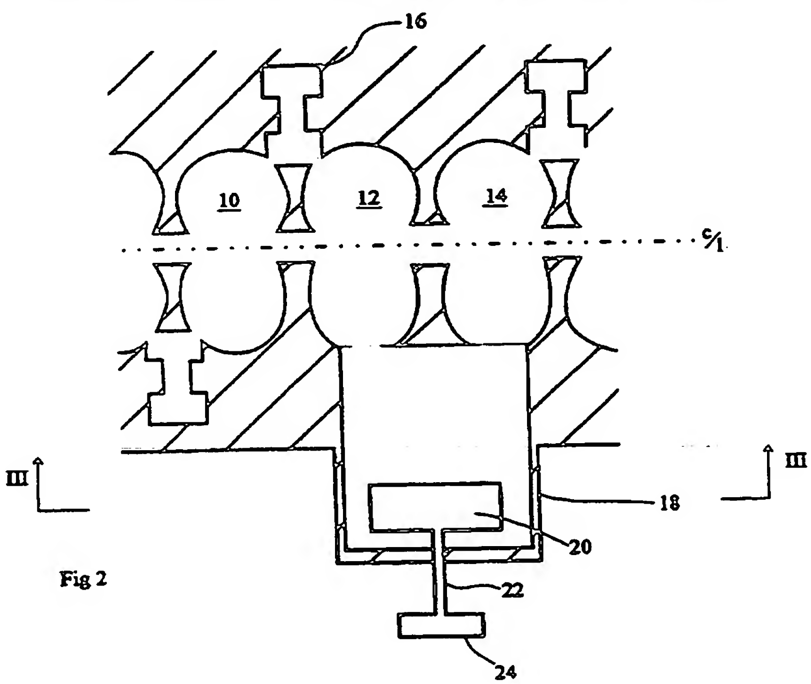

Fig 2

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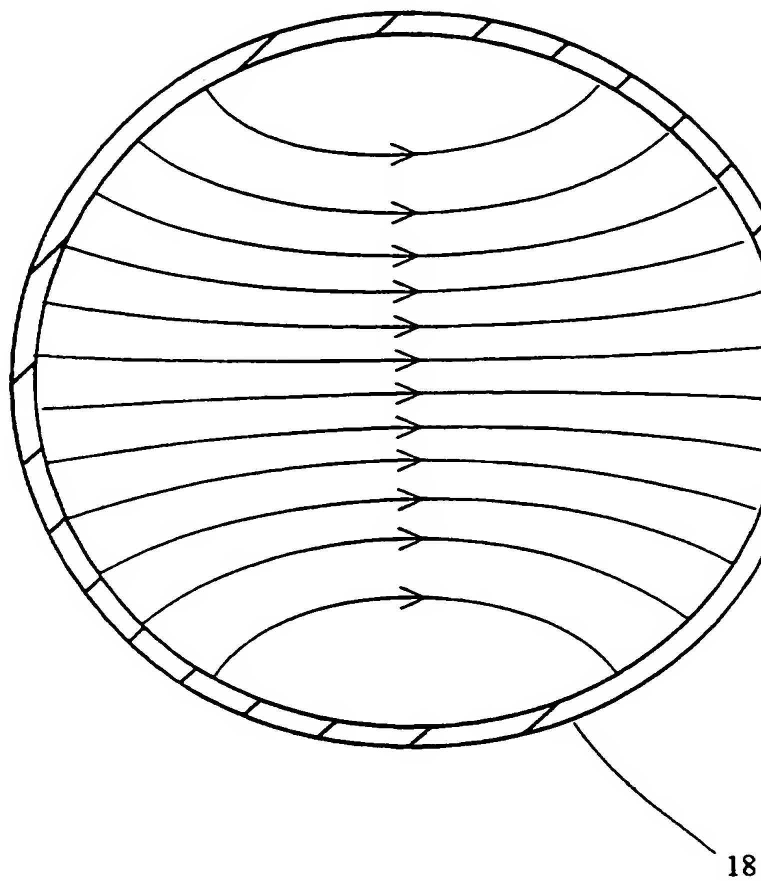
The claims were filed later than the filing date within the period prescribed by Rule 25(1) of the Patents Rules 1995

Fig 1



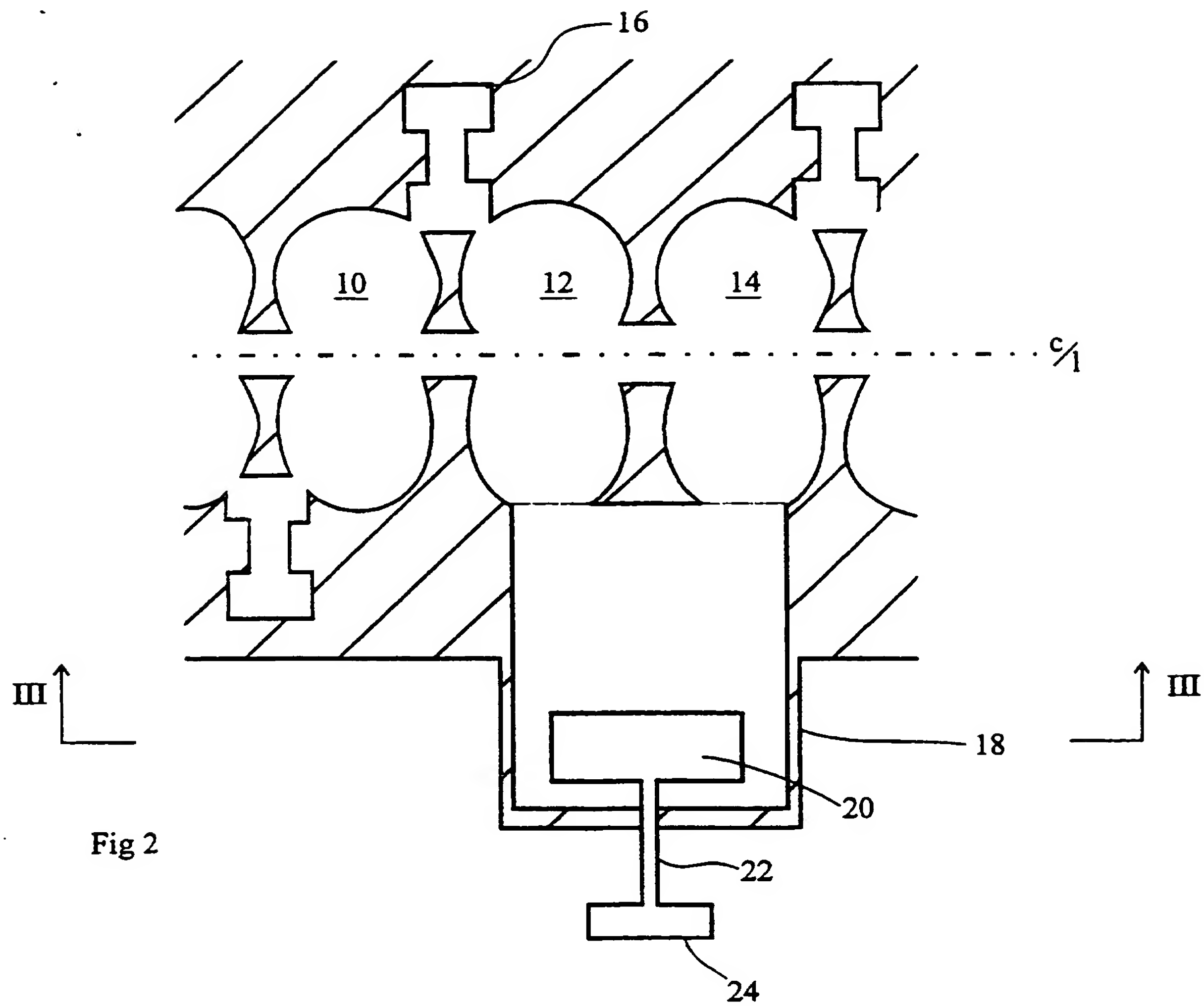
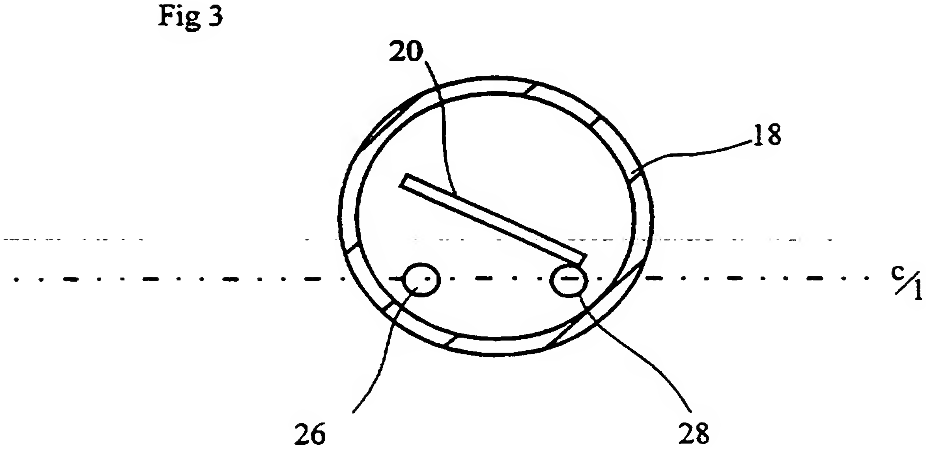


Fig 2

Fig 3



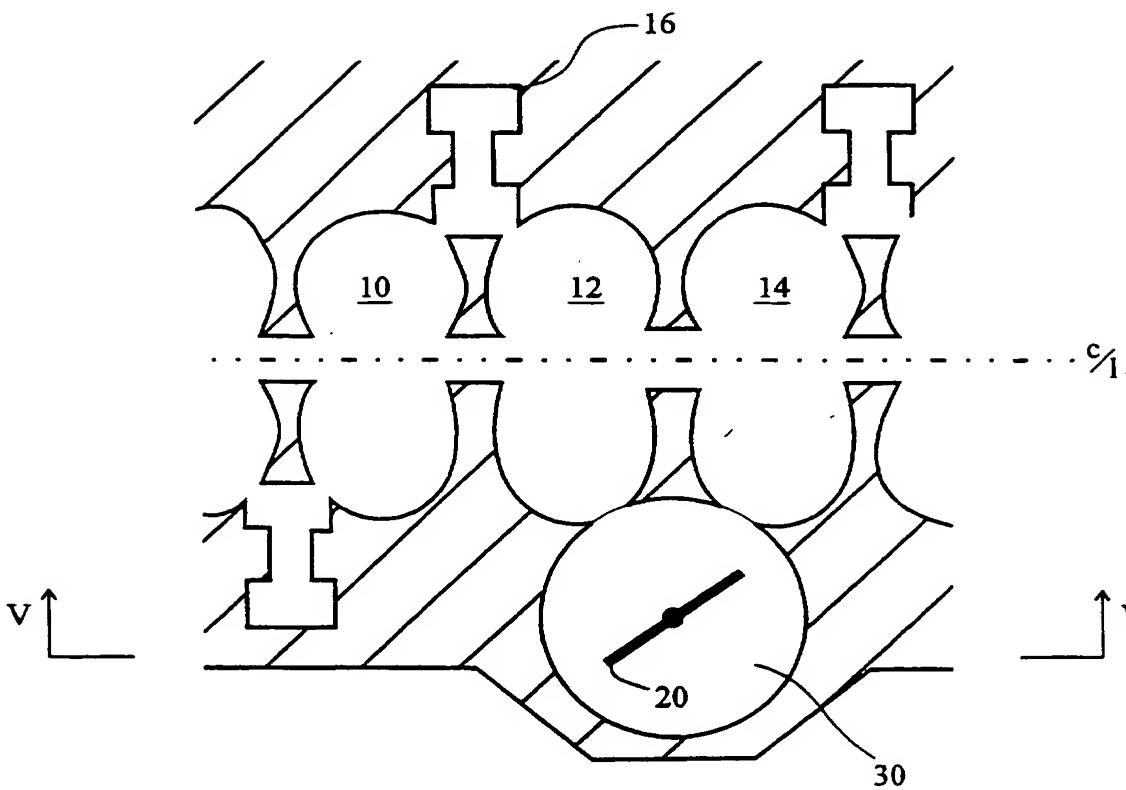
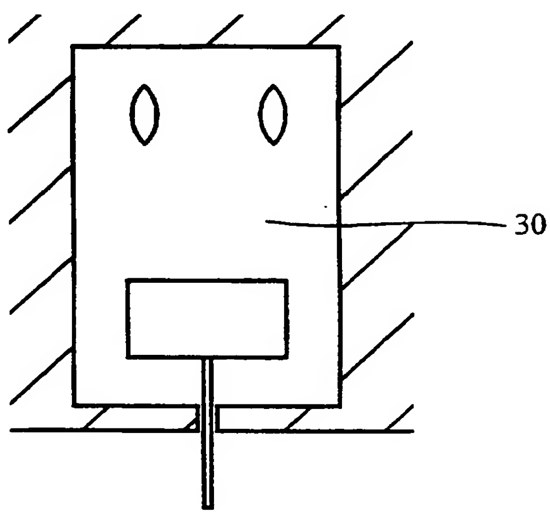


Fig 4

Fig 5



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LINEAR ACCELERATOR

The present invention relates to a linear accelerator.

Linear accelerators, particularly of the standing wave design, are known for use in X-Ray generation as a source of an electron beam. This beam can be directed to an X-ray target which then produces suitable radiation. A common use for such X-rays is in the medical treatment of cancers etc.

It is often necessary to vary the incident energy of the electron beam on the X-ray target. This is particularly the case in medical applications where a particular energy may be called for by the treatment profile. Linear standing ware accelerators comprise a series of accelerating cavities which are coupled by way of coupling cavities which communicate with an adjacent pair of accelerating cavities. According to US-A-4382208, the energy of the electron beam is varied by adjusting the extent of coupling between adjacent accelerating cavities. This is normally achieved by varying the geometrical shape of the coupling cavity.

This variation of the geometrical shape is typically by use of sliding elements which can be inserted into the coupling cavity in one or more positions, thereby changing the internal shape. There are a number of serious difficulties with this approach. Often more than one such element has to be moved in order to preserve the phase shift between cavities at a precisely defined value. The movement of the elements is not usually identical, so they have to be moved independently, yet be positioned to very

great accuracy in order that the desired phase relationship is maintained. Accuracies of ± 0.2mm are usually required. This demands a complex and high-precision positioning system which is difficult to engineer in practice. In those schemes which have less than two moving parts (such as that proposed in US Patent 4,286,192), the device fails to maintain a constant phase between input and output, making such a device unable to vary RF fields continuously, and are thus reduced to the functionality of a simple switch. They are in fact often referred to as an energy switch.

Many of these schemes also propose sliding contacts which must carry large amplitude RF currents. Such contacts are prone to failure by weld induced seizure, and the sliding surfaces are detrimental to the quality of an ultra high vacuum system. Issues of this nature are key to making a device which can operate reliably over a long lifetime.

The nature of previous proposed solutions can be summarised as cavity coupling devices with one input and one output hole, the whole assembly acting electrically like a transformer. To achieve variable coupling values the shape of the cavity has had to be changed in some way, by means of devices such as bellows, chokes and plungers. However the prior art does not offer any device which can vary the magnitude of the coupling continuously over a wide range by means of a single axis control, whilst simultaneously maintaining the phase at a constant value.

The present state of the art is that such designs are accepted as providing a useful way of switching between two predetermined energies. However, it is very difficult to obtain a reliable variable energy accelerator using such designs.

A good summary of the prior art can be found in US Patent No. 4,746,839.

The present invention therefore provides a standing wave linear accelerator, comprising a plurality of resonant cavities located along a particle beam axis, at least one pair of resonant cavities being electromagnetically coupled via a coupling cavity, the coupling cavity being substantially rotationally symmetric about its axis, but including an element adapted to break that symmetry, the element being rotatable within the coupling cavity, that rotation being substantially parallel to the axis of symmetry of the coupling cavity.

In such an apparatus, a resonance can be set up in the coupling cavity which is of a transverse nature to that within the accelerating cavities. It is normal to employ a TM mode of resonance with the accelerating cavities, meaning that a TE mode, such as TE_{111}, can be set up in the coupling cavity. Because the cavity is substantially rotationally symmetric, the orientation of that field is not determined by the cavity. It is instead fixed by the rotational element. Communication between the coupling cavity and the two accelerating cavities can then be at two points within the surface of the coupling cavity, which will then "see" a different magnetic field depending on the orientation of the TE standing wave. Thus, the extent of coupling is varied by the simple expedient of rotating the rotational element.

Rotating an element within a vacuum cavity is a well known art and many methods exist to do so. This will not therefore present a serious engineering difficulty. Furthermore, eddy currents will be confined to the rotational element itself and will not generally need to bridge the element and its surrounding structure. Welds will not therefore present a difficulty.

The design is also resilient to engineering tolerances. Preliminary tests show that an accuracy of only 2dB is needed in order to obtain a phase stability of 2% over a 40° coupling range. Such a rotational accuracy is not difficult to obtain.

It is preferred if the rotational element is freely rotatable within a coupling cavity of unlimited rotational symmetry. This arrangement gives an apparatus which offers greatest flexibility.

A suitable rotational element is a paddle disposed along the axis of symmetry. It should preferably be between a half and three quarters of the cavity width, and is suitably approximately two-thirds of the cavity width. Within these limits, edge interactions between the paddle and the cavity surfaces are minimised.

The axis of the resonant cavity is preferably transverse to the particle beam axis. This simplifies the rf interaction considerably.

The accelerating cavities preferably communicate via ports set on a surface of the coupling cavity. It is particularly preferred if the ports lie on radii separated by between 40° and 140°. A more preferred range is between 60° and 120°. A particularly preferred range is between 80 and 100°, i.e. approximately 90°.

The ports can lie on an end face of the cavity, i.e. one transverse to the axis of symmetry, or on a cylindrical face thereof. The latter is likely to give a more compact arrangement.

Thus, the invention proposes the novel approach of coupling the RF into a special cavity operating in the TE_{111} mode. By choosing the coupling positions of the input and output holes to lie along a chord of the circle forming one of the end walls of the cavity, a special feature of the TE_{111} mode can be exploited to realise a coupling device with unique advantages. Instead of changing the shape of the cavity, this invention proposes to rotate the polarisation of TE_{111} mode inside the cavity by means of a simple paddle. Because the frequency of the TE_{111} mode does not depend upon the angle that the field pattern makes with respect to the cavity (the polarising angle),

the relative phase of RF coupled into two points is invariant with respect to this rotation, at least for 180°. At the same time, the relative magnitude of the RF magnetic fields at the two coupling holes lying along a chord, varies by up to two orders of magnitude. This property of the RF magnetic field is the basis of the variable RF coupler of this invention.

The key to the proposed device is that the moving paddle is not a device to change the shape of the cavity, as described in the prior art, but is merely a device to break circular symmetry of the cylindrical cavity. As such the paddle does not have to make contact with the walls of the cavity, nor does any net RF current flow between the paddle and the cavity wall. This makes the device simple to construct in vacuum, requiring only a rotating feed-through, which is well known technology. Alternatively, the paddle might be rotated by an external magnetic field, and so eliminate the vacuum feed-through requirements.

An embodiment of the present invention will now be described by way of example, with reference to the accompanying drawings, in which:-

Figure 1 is a view of the electric field lines of the TE_{111} cylindrical cavity mode;

Figure 2 shows a longitudinal cross-section through a standing wave linear accelerator according to a first embodiment of the present invention; and

Figure 3 shows a section on III-III of Figure 2;

Figure 4 is a longitudinal cross-section through a standing wave linear accelerator according to a second embodiment of the present invention; and

Figure 5 is a section on V-V of Figure 4.

In a standing wave accelerator the device could be implemented as shown in the first embodiment, Figures 2 and 3. These show three on-axis accelerating cells 10, 12, 14 as part of a longer chain of cavities. The first and second accelerating cavities 10, 12 are coupled together with a fixed geometry coupling cell 16, which is known art. Between the second and third on-axis cavities 12, 14, the fixed geometry cell is replaced by a cell 18 according to the present invention. This cell 18 is formed by the intersection of a cylinder with the tops of the arches that make up the accelerating cells thus forming two odd shaped coupling holes 26, 28. To function as intended, these holes should ideally be along a (non-diametrical) chord of the off-axis cylinder, which implies that the centre line of the cylinder is offset from the centre line of the accelerator, as shown in the Figure 3. These coupling holes are in region of the cavity where magnetic field dominates, and so the coupling between cells is magnetic. However unlike the fixed geometry cells there is now a simple means of varying the coupling between cells, and consequently the ratio of the RF electric field in the second and third on-axis cells. The strength of the coupling (k) depends upon the shape of the hole and the local value of the RF magnetic field at the position of the hole. The on-axis electric field varies inversely with the ratio of the k values. Hence:-

$$\frac{E_1}{E_2} = \frac{k_2}{k_1}$$

The magnetic field pattern close to the end wall, means that if the coupling holes lie along a chord, k_1 will increase as k_2 decreases.

A rotatable paddle 20 is held within the cavity 18 by an axle 22 which in turn extends outside the cylindrical cavity 18. As shown in Figure 2, the axle has a handle 24 to permit rotation of the paddle 20, but the handle could obviously be replaced by a suitable actuator.

• The paddle serves to break the symmetry of the cavity 18, thus forcing the electric lines of field to lie perpendicular to the paddle surface.

The end result is a device which has just one simple moving part, which upon rotation will provide a direct control of the coupling between cells, whilst at the same time keeping the relative phase shift between input and output fixed, say at a nominal π radians. The only degree of freedom in the system is the angle of rotation of the paddle. In a typical standing wave accelerator application this would only have to be positioned to the accuracy of a few degrees. Such a control would allow the energy of a linear accelerator to be adjusted continuously over a wide range of energy.

According to the second embodiment, shown in Figures 4 and 5, the coupling cavity 30 is still transverse to the longitudinal axis of the accelerating cavities, but intersects with accelerating cavities 12, 14 along a cylindrical face thereof. Thus, the axes of the accelerator and of the coupling cavity do not intersect, but extend in directions which are mutually transverse. The paddle 20 etc. is unchanged. Otherwise, the operation of this embodiment is the same as the first.

It will of course be appreciated by those skilled in the art that the above-described embodiment is simply illustrative of the present invention, and that many variations could be made thereto.

CLAIMS

1. A standing wave linear accelerator, comprising a plurality of resonant cavities located along a particle beam axis, at least one pair of resonant cavities being electromagnetically coupled via a coupling cavity, the coupling cavity being substantially rotationally symmetric about its axis, but including an element adapted to break that symmetry, the element being rotatable within the coupling cavity, that rotation being substantially parallel to the axis of symmetry of the coupling cavity.

2. An accelerator according to claim 1 in which communication between the coupling cavity and the two accelerating cavities is respectively at two points within the surface of the coupling cavity.

3. An accelerator according to claim 1 or claim 2 wherein the rotational element is freely rotatable within a coupling cavity of unlimited rotational symmetry.

4. An accelerator according to any one of the preceding claims in which the rotational element is a paddle disposed along the axis of symmetry.

5. An accelerator according to claim 4 wherein the paddle occupies between a half and three quarters of the cavity width.

6. An accelerator according to any one of the preceding claims wherein the axis of the resonant cavity is transverse to the particle beam axis.

7. An accelerator according to any one of the preceding claims wherein the accelerating cavities communicate via ports set on a surface of

the coupling cavity.

8. An accelerator according to any one of the preceding claims wherein the ports lie on radii of the coupling cavity separated by between 40° and 140°.

9. An accelerator according to any one of the preceding claims wherein the ports lie on radii of the coupling cavity separated by between 60° and 120°.

10. An accelerator according to any one of the preceding claims wherein the ports lie on radii of the coupling cavity separated by between 80 and 100°.

11. An accelerator according to any one of the preceding claims wherein the ports lie on an end face of the cavity.

12. An accelerator according to any one of claims 1 to 10 wherein the ports lie on a cylindrical face of the cavity.

13. An accelerator substantially as described herein with reference to and/or as illustrated in the accompanying figures 2 to 5.

The Patent Office

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Application No: GB 9802332.8
Claims searched: all

Examiner: Russell Maurice
Date of search: 30 October 1998

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): H1D (DL, DKGA, DKGB, DKGC, DKAK)

Int Cl (Ed.6): H05H (7/12, 7/14, 7/18, 7/20, 9/00, 9/04)
H01J (23/213, 23/18, 23/20, 23/207)

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
Y	GB 0599129 A	Sperry Gyroscope Company Inc. (see figure 2 region around parts 88 and page 2 lines 6 et seq)	4, 5
Y	GB 0530785 A	Leland Stanford Junior Uni.(see figure 1 parts 36, 37 and page 2 lines 72 et seq)	4, 5
X, Y	US 4629938 A	Whitham (whole document see figure 1)	X: 1, 2, 3, 6 Y: 4, 5

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.